Project Report
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Initial Evaluation of the Oregon State University Planetary Boundary Layer Column Model for ITWS Applications

J.L. Keller
F.W. Wilson
C.B. Smith

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Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

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16. Abstract

The Federal Aviation Administration (FAA) Integrated Terminal Weather System (ITWS) is supporting the development of products important for air traffic control in the terminal area. Some ITWS products will allow air traffic managers to anticipate operationally significant short-term (0–30 min) changes in ceiling and visibility (C&V) and aircraft separations necessary to avoid encounters with wake vortices. Development of such products exploits data that will by available from new FAA terminal area sensor systems. These sensor systems include Terminal Doppler Weather Radar (TDWR), Next Generation Weather Radar (NEXRAD), the Meteorological Data Collection and Reporting System (MDCRS), and the Automated Surface Observing System (ASOS).

A Dynamic Atmospheric Vertical Structure Nowcast System (DAVS-NS) is being developed that will add value to ITWS by providing current analyses and short-term forecasts of the vertical atmospheric structure focused at specific sites within the terminal domain. This report summarizes the initial evaluation of the Oregon State University one-dimensional boundary layer model for its potential role within a DAVS-NS.

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1. INTRODUCTION

The vertical structure of the atmosphere in the lower one or two kilometers of the atmosphere is important in determining whether the atmospheric environment can support phenomena responsible for Ceiling and Visibility (C&V) degradation or long-lived wake vortices. High vertical resolution will be required to resolve many of these phenomena properly: from less than a meter to a few tens of meters, depending on the phenomena (Keller, 1994). As well, it will be necessary to have temporal resolution much higher than that which has been traditionally available in operational meteorology. Estimates of the atmosphere's vertical temperature, moisture and wind structure (the so-called State-of-the-Atmosphere Variables, or SAVs) could be obtained by balloon soundings. This measurement process is not well suited for continuous, automated updates. Recent research in numerical weather prediction has yielded the one-dimensional boundary layer "column" model as a possible alternative.

One-dimensional Planetary Boundary Layer (PBL) models have been designed using physically-based governing equations to diagnose and forecast the state of a single column of the atmosphere, with special attention to the lowest one to two kilometers. Besides SAVs, these models often include derived atmospheric variables also important to aviation, such as turbulent kinetic energy and liquid water content, for which profiles cannot be easily measured. PBL column models can be particularly effective when local surface forcing, resulting from the vertical redistribution of radiative surface heating or cooling, dominates. Turbulent eddies, generated at the surface as part of the so-called Soil-Vegetation Atmospheric Transfer (SVAT) process, provide the dominant vehicle for this redistribution.

Since column models cannot directly model forcing resulting from atmospheric dynamic processes such as horizontal advection, the most straightforward application of these models is for situations with light winds when advection is small. At these times the dominant forcing mechanisms, resulting mainly from surface heating, can be reasonably handled within the constrained geometry of a one-dimensional vertical column. Several important weather phenomena responsible for operationally significant weather conditions in the terminal area can be found in this dynamically weak environment. Specific phenomena include morning and evening wake vortex behavior (Greene, 1986), and the formation, lifting and burn off of radiation fog (Fitzgarrald and Lala, 1989; Tardiff and Zwack, 1994). Other phenomena for which horizontal advection can be significant, such as marine stratus, can still be addressed by a one-dimensional column model if the forcing by horizontal advection is not changing rapidly in time.

We are investigating the possibility of developing a Dynamic Atmospheric Vertical Structure Nowcast System (DAVS-NS) to provide updated and short-term forecasts of the vertical atmospheric profile above an ITWS site. The core of this system would be a PBL column model. Our approach involves using a combination of sensing technology and analysis techniques that have proven successful in several research programs. We have

identified two PBL column models that have been developed and used for site-specific forecasting applications: the Oregon State University PBL column model (Ek and Mahrt, 1993) and the Meteo France / Paul Sabatier University COuche Brouillard Eau Liquide (COBEL) model (Bergot and Guedalia, 1994). Because of its easy accessibility, widespread use and acceptance we have begun to evaluate the OSU model for its potential role as an ITWS PBL column model. The OSU model has provided dependable service in several field experiments providing vertical atmospheric structure information with a vertical resolution as fine as 10 m.

A separate flux-forced version of the OSU model, FFOSU, has been created by modifying the source code to accept measured, rather than modeled, surface fluxes of temperature, moisture and momentum. The primary motivation for these modifications, discussed in detail later in this report, is to reduce the error in the modeled fluxes associated with characterizing the nature of SVAT processes over complex airport area surfaces. Potentially, an operational DAVS-NS might comprise both the FFOSU model, that would provide a dynamically adjusting current atmospheric profile, and another variant of the OSU model that would produce a short-term atmospheric profile forecast.

Both the original OSU and FFOSU models will be thoroughly evaluated using data to be collected during the 1994-95 combined National Aeronautics and Space Administration (NASA) wake vortex project and ITWS test bed at Memphis International Airport (MEM). Data from the MEM test bed will include near-surface flux data measured by sensors mounted on a tower platform at heights of 5 and 45 m and numerous soundings.

In preparation for the MEM tests, these models have been evaluated using data sets from two STORM - Fronts Experiment Systems Test (STORM-FEST) Intensive Observation Periods (IOPs). Data from STORM-FEST (1 February - 15 March 1992) provides one of the few publicly available archives that contain both surface fluxes and soundings. This report primarily discusses the performance of the original OSU and FFOSU models for two case studies using archived STORM-FEST data.

2. DESCRIPTION OF THE OSU COLUMN MODEL

The OSU models the local tendencies of the SAVs of horizontal momentum, potential temperature and water vapor mixing ratio in the atmosphere using governing equations of the general form

$$\frac{\partial}{\partial t}\overline{\xi} = -\frac{\partial}{\partial z}\left(\overline{w'\xi'}\right) \quad + \text{ non local, larger-scale forcing terms.}$$

Here w is an instantaneous value of the vertical motion that can be expressed by its mean (typically five-minute averages) and the deviation from this mean as

$w = \overline{w} + w'$ and $\overline{\xi} + \xi'$.

A positive correlation, $(w'\xi' > 0)$ between perturbations in the vertical motion, w' and some quantity ξ' (e.g., temperature, moisture, etc.) corresponds to upward vertical fluxes of the quantity ξ.

The over-bar shown in the first term on the right-hand side of the governing equation indicates an ensemble space-time average comprising the forcing by vertical fluxes due to turbulent eddies. Eddies of concern in this idealized representation have spatial scales typically on the order of a few 100s of meters, temporal scales less than one minute, and are random in their behavior with no preferred directional structure. Further inspection of the governing equation reveals that it is the *vertical slope of the eddy fluxes* which forces the evolution of the larger-scale ensemble-averaged atmospheric state. Forcing of the mean atmospheric state in this way becomes more accurate the more the actual turbulence in the atmosphere resembles this idealized, homogeneous condition (Batchelor, 1953). Examples of direct forcing of the larger-scale ensemble averaged atmosphere include advection and adjustments by the horizontal wind to changes in the pressure field.

Vertical fluxes in the OSU model are parameterized using a variation of the commonly used gradient transfer technique (Troen and Mahrt, 1986). This type of parameterization is generally considered appropriate for modeling well-mixed PBLs. Larger-scale forcing due to vertical advection and the horizontal wind (approximated by the geostrophic wind) are provided to the OSU model as external parameters.

Other potentially important forcing, net radiative clear-air cooling and horizontal advection are not accounted for explicitly. Net radiative clear-air cooling can be important during light wind situations in the lowest few tens of meters. Neglecting this forcing mechanism may be a source of error especially for nocturnal boundary layers. Advective forcing occurs when wind flows parallel to gradients of temperature, moisture, etc. Horizontal advection only becomes a problem in dynamic situations, such as during frontal passages, when it may change rapidly in time. Most anticipated applications of a

DAVS-NS will be for light winds and weak horizontal gradients when local forcing associated with surface radiative heating dominates.

2.1 SVAT Model Surface Fluxes

The OSU model has been developed and studied for general numerical weather prediction uses. Surface fluxes providing the lower boundary forcing are estimated by the OSU model's SVAT model. To estimate realistic surface fluxes, SVAT models require extensive soil and surface information that, ideally, would be obtained by a suite of in situ sensors. Examples of these measurements include:

- surface type, roughness length and ("skin") temperature
- soil type and vertical profiles of soil temperature and moisture
- surface water content (dew, water, ice and snow coverage)
- vegetation canopy water content, capacity and transpiration

Measuring these quantities is relatively easy for homogeneous surfaces, but becomes very difficult over complex surfaces. For this reason, most column model studies have been performed in regions with homogeneous surfaces such as plowed fields.

2.2 Directly Measured Surface Fluxes

To use a column model in an area with a complex surface, such as an airport, it is necessary to find a way to obtain regionally representative estimates of the surface fluxes. Designing an effective in situ sensor system to measure the necessary soil and surface characteristics over such a complex surface would be daunting. Measured fluxes provide a possible means for obtaining regionally representative surface flux estimates. Field experiments have revealed that the region of influence on the measured fluxes can be controlled by the selection of the height of the flux measurement system (Horst and Weil, 1992). Thus, the height of the instrument package becomes a control mechanism for area averaging. At least a 10 Hz sampling rate for wind, temperature and moisture is usually required to support the direct computation of the correlation that provide estimates of turbulent fluxes. Correct estimates of net vertical transport rates require time averaging the covariance over periods from 5 to 20 minutes, depending on the meteorological situation (Kaimal and Finnagin, 1994).

A second version of the OSU model, FFOSU, was conceived that would use the measured surface fluxes rather than those provided by its own SVAT module. This version was created by modifying the OSU model's original software.

2.3 Model Input Parameters

Besides surface and soil information, the OSU model is initialized using vertical SAV profiles that can be obtained from either balloon or model grid point soundings. Usually, this initial input profile is observed on a rather coarse grid and is interpolated to a finer model grid. The model then generates additional detail from the forcing terms. Table 1 summarizes the parameters and data required to initialize both the OSU and FFOSU models. Table 2 summarizes the additional parameters and data required to initialize the OSU model.

Table 1. Control parameters required for both OSU and FFOSU model initialization.

PARAMETER	DESCRIPTION
Vertical Resolution	Maximum: 10 m from surface to height of 100 m
Time Step	10 m resolution requires 15 s
Duration of Model Run	
Site Latitude, Longitude	
Site Time Zone	Defined as LT minus GMT (LT = Local Time)
Month	Defined as 1 - 12
Day of Month	
Time of Initialization	In GMT
Vertically Averaged PBL Geostrophic Wind	Part of larger-scale forcing; can be specified to vary in either time or altitude
Air Temperature Profile	Celsius
Vertical Motion Profile	Used to calculate larger-scale vertical advection
Moisture Profile	Mixing ratio in gm/kg

Table 2. Additional soil and atmospheric parameters required to initialize the OSU model.

PARAMETER	DESCRIPTION (when necessary)
Momentum Roughness Length	
Roughness Length for Heat	
Vegetation Height	
Surface Albedo	
Surface Pressure	In mb
Fractional Cloud Cover	Defined as 0.0 - 1.0
Canopy Water Content	In meters
Canopy Water Capacity	In meters
Soil Type	
Vegetation Wilting Point	
Shading Factor	
Plant Coefficient	
Soil Depth	Depth of soil model
Soil Water Content	
Air Dry Value	Available surface moisture
Soil Temperature	
Precipitation Start Time	Hours from beginning of run
Precipitation End Time	Hours from beginning of run
Precipitation Rate	In mm/hr
Depth of Snow	In mm

3. MODEL EVALUATION WITH STORM-FEST DATA

Very few publicly available data archives from field tests exist in which both surface fluxes and collocated atmospheric soundings were taken concurrently. An approximation for such a data set is the winter 1992 STORM-FEST experiment over the fairly homogeneous region of Northeast Kansas. In a proof of concept for the FFOSU model, we have conducted a preliminary evaluation using archived STORM-FEST data.

3.1 The STORM-FEST Data Sets

The STORM-FEST data used for the cases to be discussed below were primarily from the National Center for Atmospheric Research (NCAR) Atmosphere-Surface Turbulent Exchange Research facility (ASTER) array and Cross-chain Loran Atmospheric Sounding System (CLASS) soundings (Figure 1). It was at the NCAR ASTER field facility array where the surface (4 m) fluxes needed for the evaluation of the FFOSU model were measured. A problem common with the STORM-FEST data sets is that the CLASS site was not collocated with the ASTER flux measurement site near Sabetha, KS but is some 25 km to the west. To reconcile the resulting discrepancy in the vertical continuity, the temperature was adjusted in the vertical, assuming a well-mixed condition between the surface and the top of the PBL at the ASTER site. The structure in the free atmosphere was not changed. Figure 2 shows the original CLASS potential temperature sounding and the resulting adjusted profile for 1300 LT (13 LT) 12 March. Observations indicate that the well-mixed assumption is reasonable for the cases chosen.

STORM-FEST was designed to gather data during midwest winter storms that would be expected to be very dynamic. Under these conditions, horizontal advection can be large and vary rapidly in time. Since we are interested in cases with weak advection, we selected the light wind STORM-FEST cases of the 19 February and 12 March 1992 IOPs. At the time these analyses were performed, no data were available that could be used to estimate the mean (large scale) vertical motion. The vertical motion was simply set to zero, which is a reasonable assumption given the generally weak dynamics. The large-scale wind field was estimated from the CLASS wind sounding near the top of the mixed layer and was set to be constant in time.

3.2 Method of Evaluation

The primary purpose of this exercise is to demonstrate that the FFOSU concept is a sound extension of the OSU model. The ASTER flux data have been compared to the fluxes generated by the original OSU model's surface layer SVAT parameterization and were used directly to "force" the FFOSU model. SVAT fluxes compared reasonably well to measurements; however, there were differences in detail, especially for the 19 February IOP. Small differences between the measured and SVAT flux estimates should be expected because of slight differences in processing of model output.

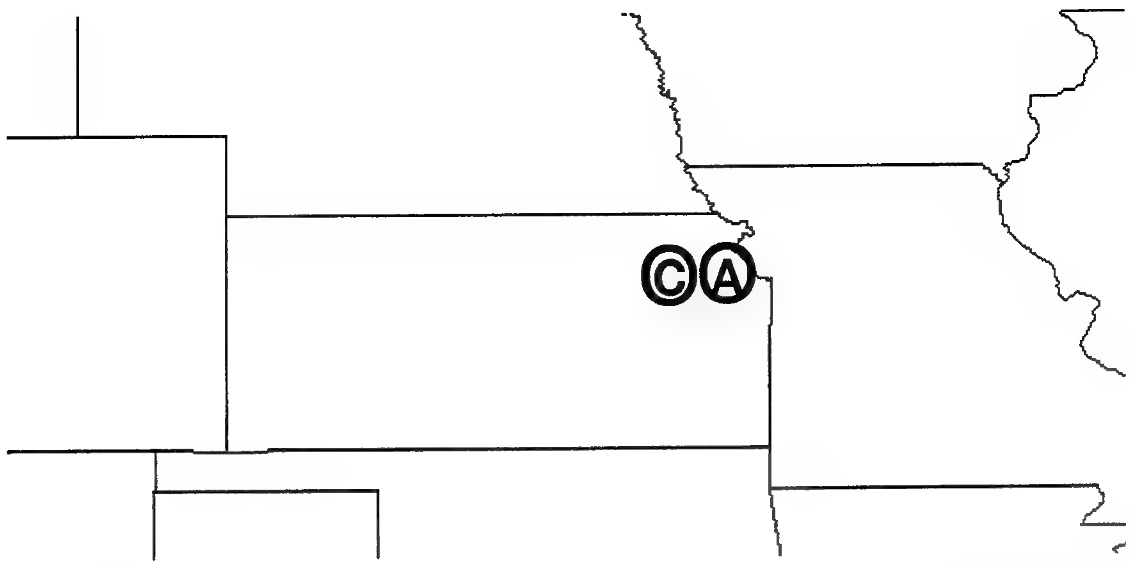

Figure 1. Location of the STORM-FEST ASTER boundary layer array Ⓐ and nearest CLASS site Ⓒ.

We have used two methods to evaluate the performance of these models. The first evaluation involves the comparison of the five-minute time series of modeled temperature and moisture at the first grid point (10 m) with the five-minute averaged 1 Hz sensor observations that were at the 10 m level of the ASTER tower. Units for temperature, T, are in °C and moisture (water vapor mixing ratio), q, in gm/m^3. The second evaluation involved the comparison of the model-generated vertical soundings with the CLASS soundings taken after the sounding used to initialize the model. In this case, we used potential temperature, θ, in °C and mixing ratio, q, in units of gm/kg.

Potential temperature, rather than temperature, is often used for soundings because potential temperature accounts for the expected temperature changes with height due to the effect of changing atmospheric pressure. Potential temperature is defined as

$$\theta = T(p_0/p)^{0.286}$$

where T is temperature and p_0 is a reference pressure (usually 1000 mb) that in this study is set equal to the surface pressure so that near the surface the temperature and the potential temperature are the same. For the situation of a well-mixed boundary layer, the potential temperature would be expected to be constant with height.

Potential temperature is also a useful quantity for revealing atmospheric vertical stratification; that is, how the resistance of the atmosphere to vertical motion varies with height. Vertical potential temperature structure can thus be viewed, albeit inversely proportional ($\theta \sim 1/\rho$), much like the variation of density with height. Layers where potential

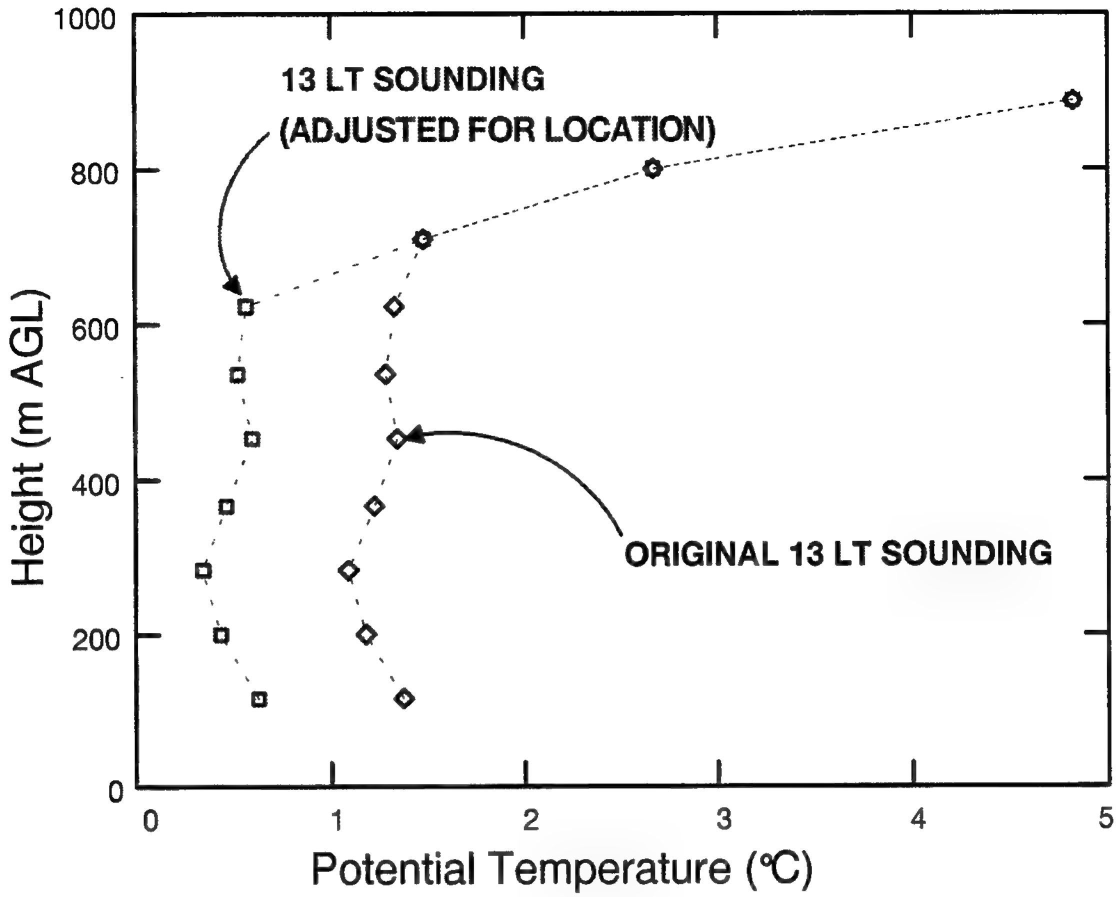

Figure 2. CLASS potential temperature profiles observed at 13 LT 12 March 1992 before and after adjusting by 0.75 °C.

temperature (density decreases) increases with altitude are convectively stable; where potential temperature decreases (density increases), convectively unstable. Layers where the potential temperature change with altitude approaches zero are described has having neutral stratification. The situation is changed somewhat if the atmosphere is very moist or cloudy and one must consider unstable stratification with respect to moist convection.

While the 10 m water vapor mixing ratio is generally expressed in terms of gm/m^3, vertical mixing ratio profiles are expressed in grams of water vapor per kilogram of dry air (gm/kg). This change of units for moisture is analogous to the change to potential temperature used above in that it becomes a conservative quantity. Without changes of state, such as evaporation or condensation, water vapor acts as a passive tracer so that the existence of a nearly constant vertical profile of water vapor mixing ratio through the boundary layer is further evidence that the PBL is well mixed.

3.3 Measured and Modeled 10 m Temperature

The evaluation starts with comparisons of modeled and observed temperatures near the surface. The modeled 10 m temperature is forced by the vertical sensible heat flux profile by using either the directly measured ASTER 4 m fluxes (FFOSU) or fluxes from the SVAT model (OSU). We begin with Figure 3 which shows the time series of the ASTER observed 4 m and SVAT surface layer vertical heat fluxes for the 19 February 1992 IOP case. The observed and modeled variation of the 10 m temperature from the original OSU and FFOSU models associated with this heat flux is show in Figure 4. Figures 5 and 6 show the same quantities, except for the 12 March 1992 IOP case.

Better agreement can be seen for the 12 March than for the 19 February case. Inspection of Figure 3 reveals that during the mid afternoon hours on 19 February the observed vertical sensible heat fluxes were significantly larger than provided by the OSU SVAT model. A particularly significant feature for the 19 February SVAT model results is that the SVAT heat fluxes decrease early, approaching zero starting just after 14 LT, while comparably small values are not actually observed until after 17 LT. Figure 4 shows that through late morning and afternoon of the 19 February IOP case, the observed 10 m temperature increased gradually until about 16 LT when it increased at a more rapid rate. Throughout the afternoon, the FFOSU model temperature tendencies more closely resembled the observations than those of the OSU model which cooled prematurely, beginning after 13 LT. This was about the same time as the OSU SVAT model fluxes approach zero. That the FFOSU temperature tendencies through the afternoon more closely follow those observed suggests the larger observed surface fluxes used in FFOSU provided for a more realistic vertical flux gradient. In the morning, when the OSU SVAT model fluxes are larger than those observed, the OSU model 10 m temperature warms more rapidly than the FFOSU model that is also too warm, but closer to the observations.

The 19 February case also provides an example of how significant horizontal advection can adversely affect column model performance. Based on examination of satellite images, there was a passage of a warm front at about 16 LT. This frontal passage is reflected in about a 1^{0}C surge in the 10 m temperature that is captured by neither model.

There was much better agreement for the 12 March case. Figure 5 reveals that during the mid afternoon hours the vertical sensible heat fluxes were significantly larger for 12 the March case than on 19 February. The OSU SVAT model fluxes were also closer to those observed for the 12 March IOP case. Where the SVAT model heat fluxes are accurate, as in the 12 March case, the temperature tendencies forecast both by the OSU and FFOSU models were close to those observed (Figure 6). Both cases show some indication of spin up, with a significant temperature increase in the first few time steps.

All these figures show evidence of model instability during initialization: a "spin up" problem. Model spin up can be caused by the use of initial conditions that are not

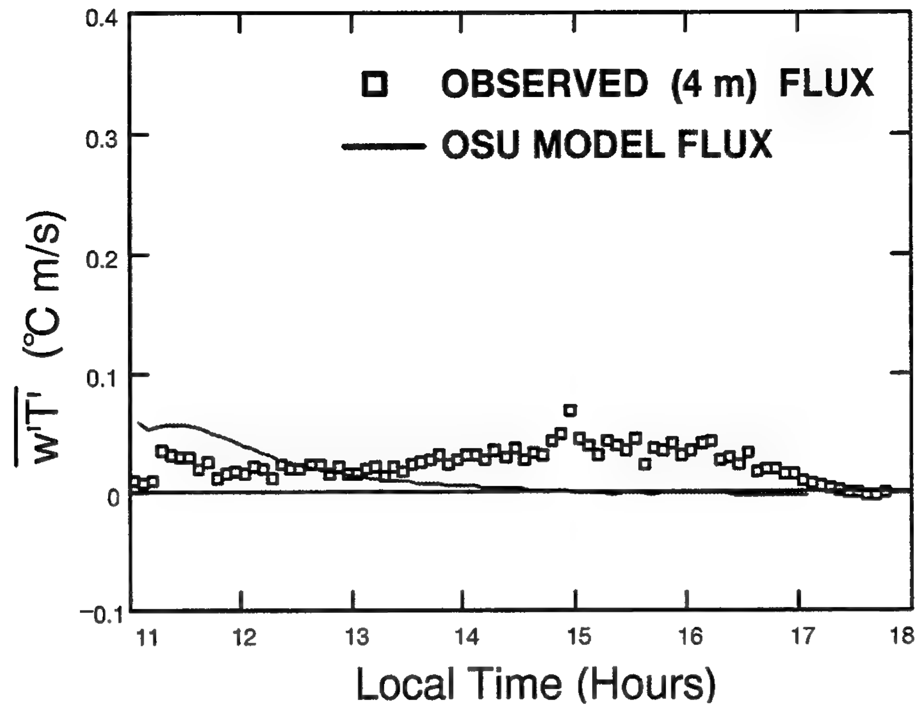

Figure 3. Observed 4 m versus modeled surface layer heat flux for 19 February 1992 at the STORM-FEST ASTER tower site.

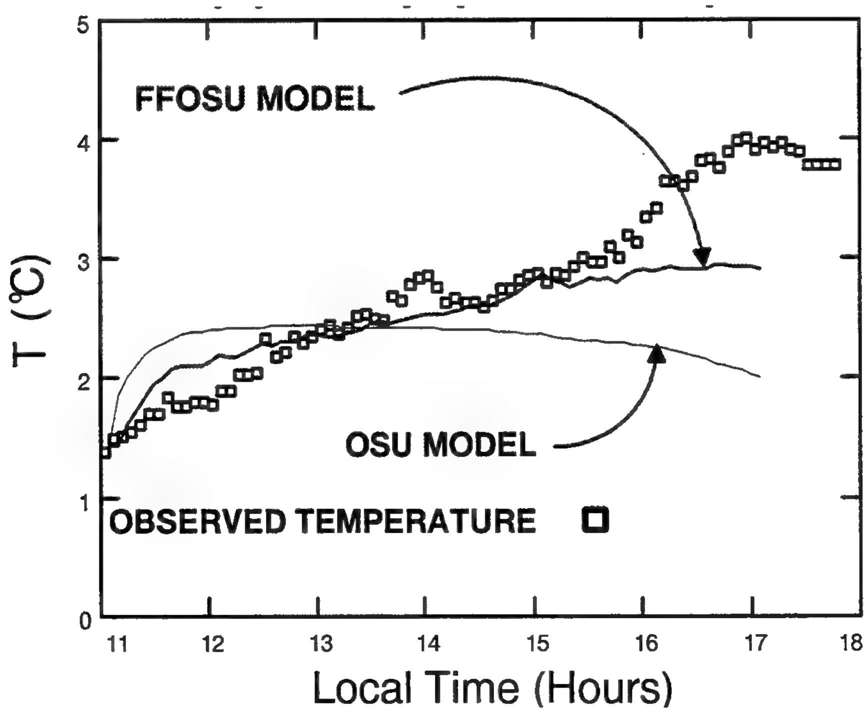

Figure 4. Observed versus original (OSU) and flux-forced (FFOSU) 10 m temperature for 19 February 1992 at the STORM-FEST ASTER tower site.

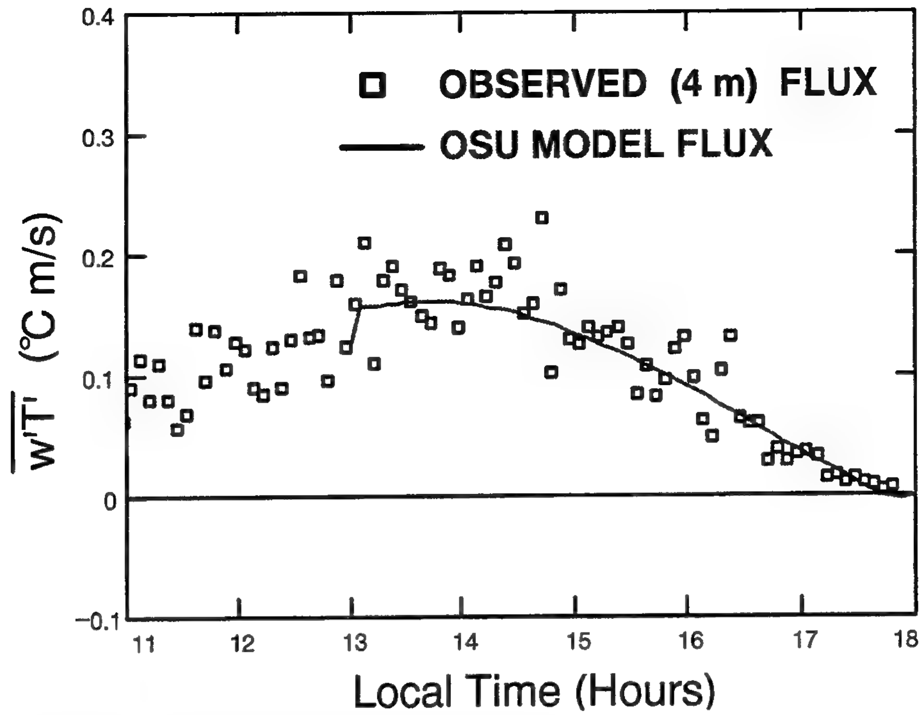

Figure 5. Observed 4 m versus modeled surface layer heat flux for 12 March 1992 at the STORM-FEST ASTER tower site.

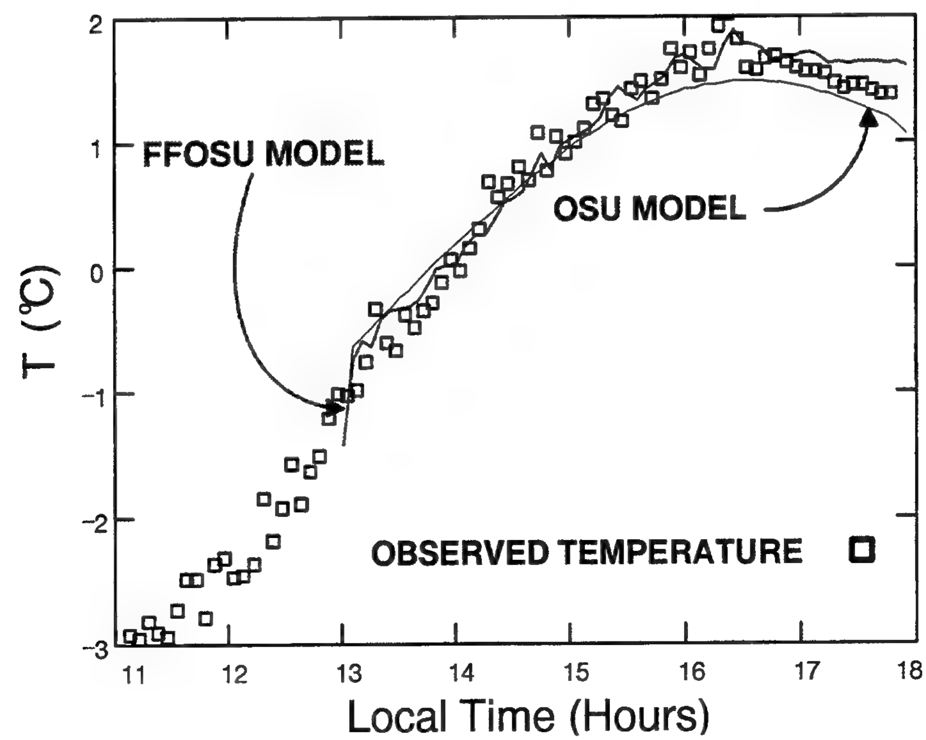

Figure 6. Observed versus original (OSU) and flux-forced (FFOSU) 10 m temperature for 12 March 1992 at the STORM-FEST ASTER tower site.

consistent with a model's internal physics; the resulting dynamical imbalance may cause highly variable time-dependent solutions until the model reaches an internally consistent state. One possible reason that spin up is seen in most of the results shown could be a consequence of the ASTER and CLASS sites not being collocated. If this is the main cause for the spin up problem, then it should be seen much less often when using the MEM data sets. Another possibility is numerical instability in the finite differencing method used to solve the differential equations. If model spin up remains a problem for the MEM data sets, we will investigate the numerical methods and other aspects of model initialization.

3.4 Measured and Modeled 10 m Moisture

The second step in the evaluation compares the modeled and observed moisture near the surface. Moisture is a fundamentally important variable in C&V. The 10 m moisture evolution is forced by the vertical water vapor mixing ratio flux profile that uses either the directly measured ASTER 4 m fluxes or those from the SVAT model as the lowest value in the profile. Figure 7 shows, as a function of time, the observed 4 m versus OSU SVAT model surface layer values of the vertical moisture (water vapor mixing ratio) flux for the 19 February 1992 IOP. The scale for the mixing ratio is similar to those used by other researchers to indicate significant variance graphically (Stull, 1988). Observed and modeled variations of the 10 m water vapor mixing ratio from the original OSU and FFOSU models associated with this moisture flux are shown in Figure 8. Figures 9 and 10 show the same quantities, except for the 12 March 1992 IOP.

The FFOSU model performed similarly for both the 19 February and 12 March cases, while the OSU model performed somewhat better for the 19 February case. Figure 7 reveals after 15 LT through the mid afternoon hours on 19 February that, while becoming becoming more variable, the observed vertical moisture fluxes increased. The OSU fluxes were forecast to decrease. The observed increase occurs within an hour of the apparent warm front passage and may be a result of decreased vertical stability that would be expected once the colder air near the surface was displaced. This would result in more efficient vertical transport. Although the observed flux is nearly zero near the end of the data stream shown, no evidence of flux reversal (often a source of dew) is evident.

The nearly constant observed 10 m water vapor mixing ratio (Figure 8) suggests that the decrease in the surface moisture flux was due to decreased turbulence rather than to the drying of the surface soil vegetation canopy. As well, the passage of the warm front resulted in no apparent significant influx of moisture. The modeled variation of the 10 m moisture from the original OSU and FFOSU models is show in Figure 8. After the initial spin up, both the OSU and FFOSU models show slight increases in water vapor mixing ratio, although the more gradual rate of increase of the FFOSU is closer to that observed. The increase in the OSU model moisture after 1530 LT is probably a manifestation of the SVAT model's effect during stable boundary layer conditions. This conclusion is supported by the slightly negative surface layer heat fluxes seen in Figure 3.

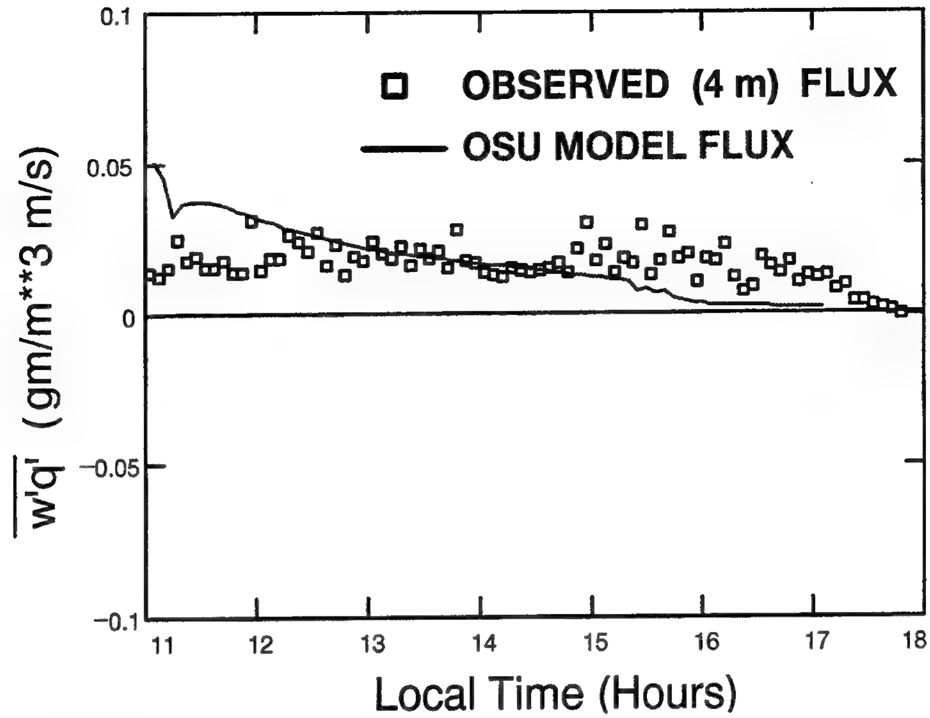

Figure 7. Observed 4 m versus modeled surface layer water vapor mixing ratio flux for 19 February 1992 at the STORM-FEST ASTER tower site.

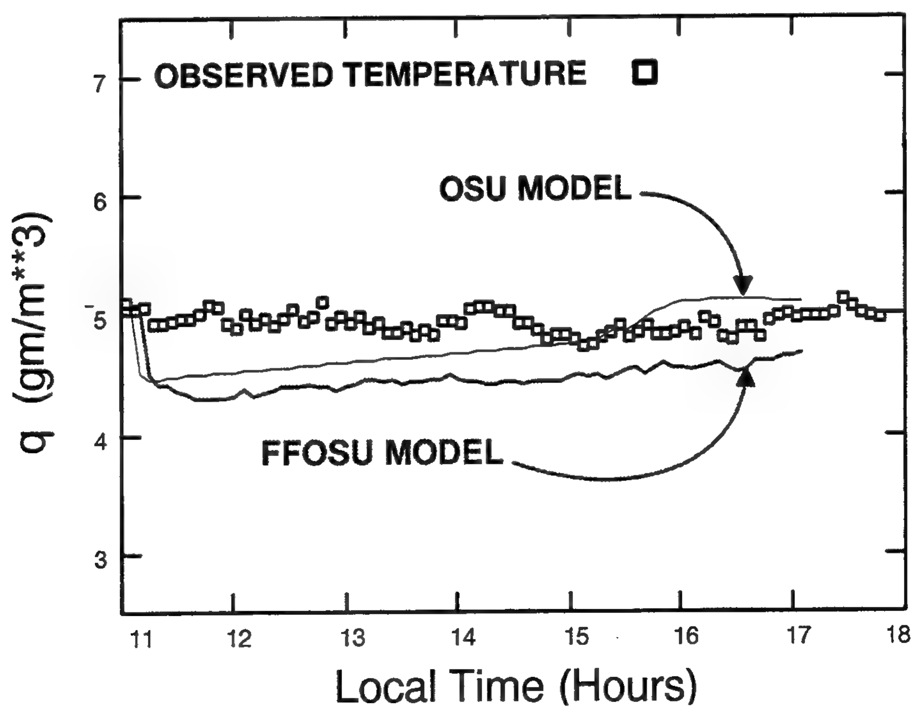

Figure 8. Observed versus original (OSU) and flux-forced (FFOSU) 10 m water vapor mixing ratio for 19 February 1992 at the STORM-FEST ASTER tower site.

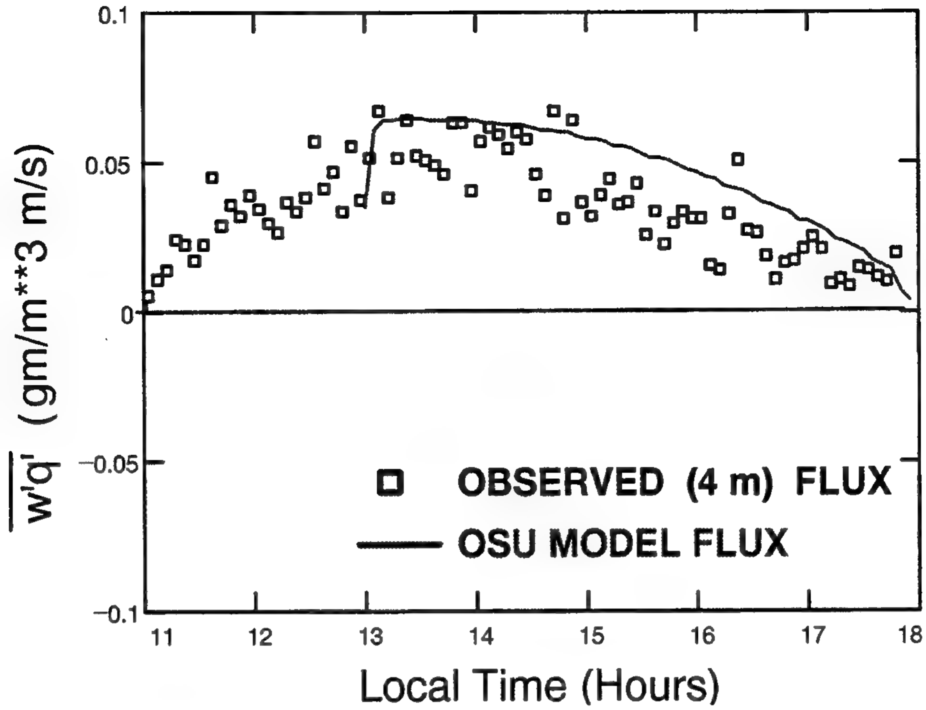

Figure 9. Observed 4 m versus modeled surface layer water vapor mixing ratio flux for 12 March 1992 at the STORM-FEST ASTER tower site.

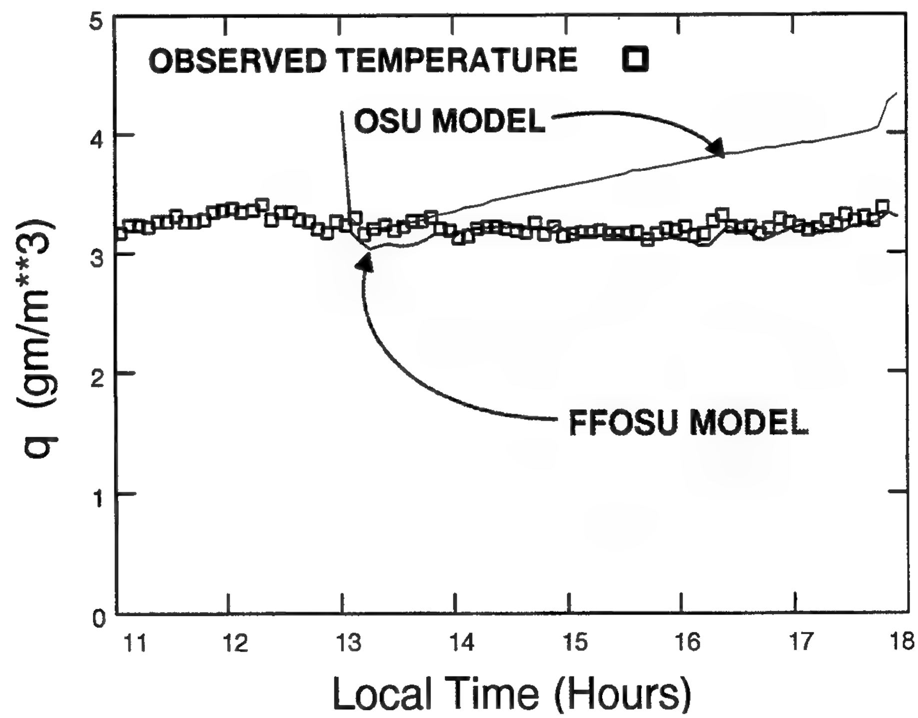

Figure 10. Observed versus original (OSU) and flux-forced (FFOSU) 10 m water vapor mixing ratio for 12 March 1992 at the STORM-FEST ASTER tower site.

Vertical moisture fluxes at the surface were significantly larger on 12 March than on 19 February (Figure 9). The OSU model moisture fluxes are biased high compared to those observed for the 12 March IOP. Inspection of Figures 8 and 10 shows that the PBL on 12 March was generally drier than on 19 February (3 versus 5 gm/m^3). Consistent with the higher moisture fluxes, the OSU model gradually moistened the lower boundary layer (10 m), while the FFOSU model kept the moisture level generally constant and closer to the observed behavior. One possible cause for the higher OSU SVAT model moisture fluxes and resulting higher mean water vapor mixing ratio is that the soil model kept the near-surface soil and vegetative canopy too moist. Again, both cases show strong evidence of spin up, with large tendencies in the first few time steps.

3.5 Measured and Modeled Potential Temperature Profiles

One of the more valuable contributions of a DAVS-NS would be its ability to provide detailed information about atmospheric vertical structure in the lower atmosphere. The vertical stratification of the atmosphere is an important quantity for defining the atmospheric environment that supports the evolution of C&V phenomena. For example, a constant potential temperature through the boundary layer indicates that it is well mixed. The existence of a stable boundary layer, where potential temperature is decreasing rapidly with height, has been identified as an important factor in limiting the longevity of wake vortices.

Our next step is to compare the observed and modeled soundings for the 12 March case. Both models were initialized using the CLASS sounding and ASTER surface data for 13 LT. Forecast profiles are compared to the equivalent observed profiles using 14 and 15 LT CLASS soundings. Due to the absence of CLASS soundings to provide the validating profiles, it was not possible to perform the same experiment for 19 February.

Figure 11 shows CLASS potential temperature (a) and water vapor mixing ratio (b) profiles observed at 13, 14 and 15 LT on 12 March 1992. A relatively shallow unstable layer ($d\theta/dz < 0$) of about 100 m can be seen near the surface. Above this layer the PBL approaches neutral instability ($d\theta/dz \sim 0$); the combination of the shallow unstable layer underlying the neutral layer allows for the PBL to be considered well mixed. Under these conditions the PBL depth is well defined. The depth of the mixed layer, indicated by the near neutral stratification, increased from just over 600 m to nearly 800 m by 14 LT and to about 900 m by 15 LT. Further evidence of a well-mixed layer is the nearly constant profile seen in the water vapor mixing ratio.

Vertical profiles of potential temperature through the boundary layer for 12 March of one-hour (a) and two-hour (b) forecasts from the OSU and FFOSU models are shown in Figure 12. Both models captured the change in the PBL thermal structure reasonably well. All differences are within a few tenths of a ^{0}C, which is close to the 0.5^0 C mean sensor error typical for balloon sounding sensors, such as those used by CLASS, so these results indicate that both models provide satisfactory temperature profiles.

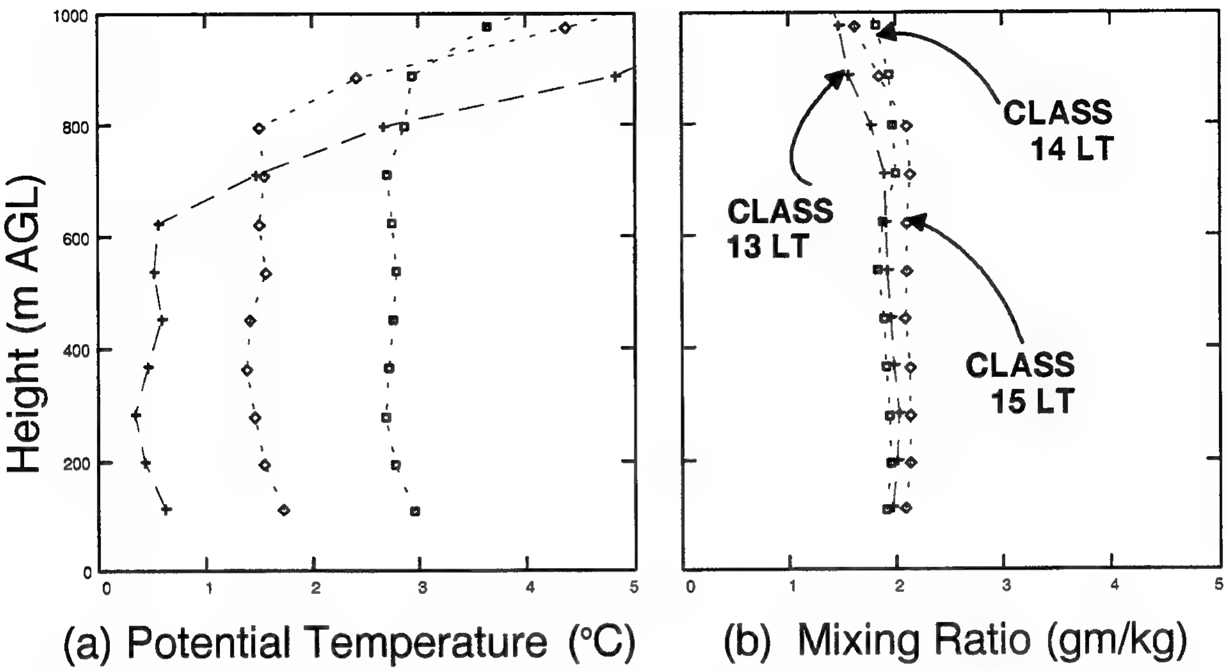

Figure 11. CLASS potential temperature (a) and water vapor mixing ratio (b) profiles (b) profiles observed at 13, 14 and 15 LT 12 March 1992.

3.6 Measured and Modeled Moisture Profiles

Consistent with the well-mixed condition revealed in the potential temperature profiles, the water vapor mixing ratio profiles for CLASS and both FFOSU and OSU models show little variation. Figure 13 shows vertical profiles of water vapor mixing ratio through the afternoon of 12 March. There is virtually no temporal change in the vertical moisture profile (within sensor error) between the CLASS soundings from 13 LT through 15 LT (Figures 13a, b). One- and two-hour forecasts of vertical moisture profiles generated using FFOSU model tendencies also show little change. These results are consistent with the nearly constant 10 m mixing ratio shown by the FFOSU model and the increase shown by the OSU model (Figure 10). Both models describe the well-mixed situation accurately, although the OSU model has biases that are consistent with the previously mentioned 10 m error. FFOSU provides accurate 10 m moisture but is also too moist aloft, although more accurate than the OSU model in this case.

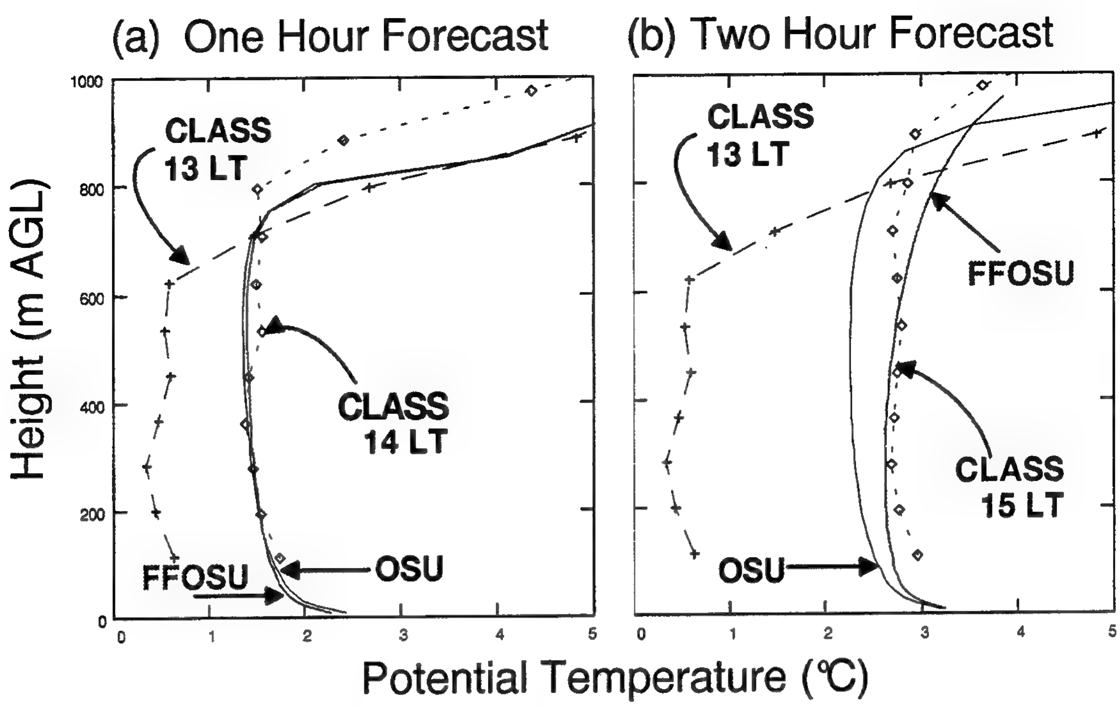

Figure 12. CLASS potential temperature profiles observed at 13, 14 and 15 LT 12 March 1992 versus one hour (a) and two hour (b) OSU and FFOSU forecasts valid at 14 and 15 LT.

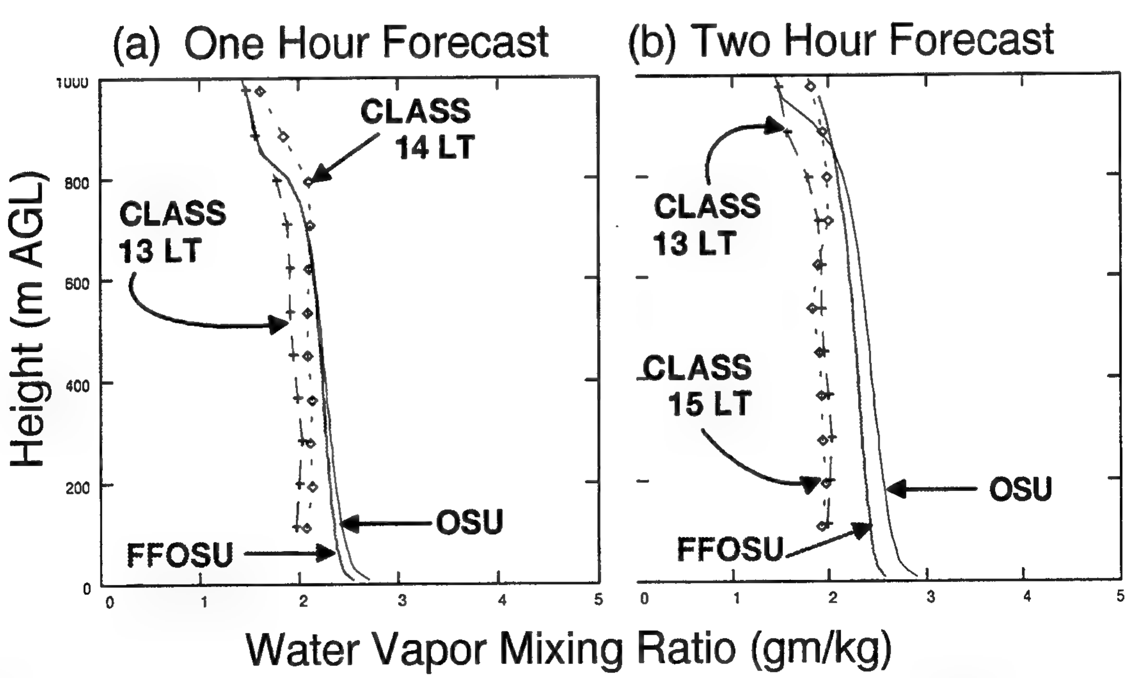

Figure 13. CLASS water vapor mixing ratio profiles observed at 13, 14 and 15 LT 12 March 1992 versus one hour (a) and two hour (b) OSU and FFOSU forecasts valid at 14 and 15 LT.

4. FUTURE WORK

STORM-FEST data sets provided an opportunity to perform a useful exercise for evaluating the potential value of the OSU PBL column model as part of a DAVS nowcast system. A complete answer to these questions can be obtained only by running the model for extended periods, at multiple sites and with ample validation data. Data collected from the Memphis ITWS and NASA wake vortex experiments will provide an opportunity to evaluate the performance of the original OSU and modified FFOSU models in an airport environment over an extended period. It will be of particular interest to see if the FFOSU model, by using observed rather than modeled surface fluxes, follows the observed atmospheric variation more closely than the OSU model.

A number of issues have been identified that will need special attention regarding the DAVS-NS ability to maintain an accurate vertical profile using measured surface fluxes. It will be possible using the MEM data sets to address some of these issues, including:

- representation of stable boundary layers
- representation and timing of evening transition from well-mixed to stable PBL
- representation and timing of morning transition from stable to well-mixed PBL
- accuracy of modeled time series of temperature and moisture at 10 m, 20 m, 30 m and 40 m (using MEM wake vortex 45 m tower sensor data)
- ability to diagnose turbulent kinetic energy (from 45 m turbulence sensor)
- evaluate magnitude of the model spin up problem.

Other more complex, long-term issues that need to be addressed in the long term include:

- decoupled elevated mixed layers
- effect of clouds above the boundary layer
- regional scale forcing
- clear-air cooling
- forecast capability

5. SUMMARY

With the recent advances in boundary layer sensor and column modeling technology, we are studying the possibility of developing an operational column model to provide continuous vertical profiles of atmospheric structure or "sounding". Several ITWS products could benefit from the information that this model could provide.

One concern for an operational column model is that of providing regionally representative surface fluxes over complex surface characteristics. An attractive possibility is to use measured surface fluxes. In this implementation, the column model would be part of a Dynamic Atmospheric Vertical Structure Nowcast System (DAVS-NS) that would use observed surface fluxes to maintain a "current sounding". Initial tests of this concept using archived data from the 1992 STORM-FEST experiment have been encouraging. The Memphis test bed data set will provide an opportunity to conduct a more thorough evaluation of the potential for this technology.

Our limited evaluation indicates that the OSU and FFOSU models provide a good starting point for the diagnosis of the PBL potential temperature and water vapor mixing ratio profiles. There is evidence of spin up instability and the possibility of undesirable sensitivity in the moisture analysis. We plan to look carefully at these factors in our future evaluations.

ACRONYMS AND ABBREVIATIONS

ASTER	Atmosphere-Surface Turbulent Exchange Research facility
CLASS	Cross-chain Loran Atmospheric Sounding System
C&V	Ceiling and Visibility
DAVS-NS	Dynamic Atmospheric Vertical Structure Nowcast System
FAA	Federal Aviation Administration
FFOSU model	Flux-Forced OSU model
Hz	Hertz
IOP	Intensive Observation Period
ITWS	Integrated Terminal Weather System
km	kilometers
LT	Local Time
m	meters
mb	millibars
mm	millimeters
MEM	Memphis International Airport
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEXRAD	Next Generation Weather Radar
OSU model	Oregon State University column model
PBL	Planetary Boundary Layer
SAV	State-of-the-atmosphere Variable
SFO	San Francisco International Airport
STORM-FEST	STORM - Fronts Experiment Systems Test
SVAT	Soil-Vegetation Atmospheric Transfer
TDWR	Terminal Doppler Weather Radar

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